Chapter 1

Key Mesoscale Phenomena

Mesoscale phenomena induce meteorological variability on Mars mostly through thermally-driven phenomena dominated by surface-atmosphere interactions (section 1.1) and waves propagating in the atmosphere (section 1.2). The former kind of phenomena has aroused the widest interest amongst Martian scientists thus far, because it exemplifies key Martian specificities compared to Earth mesoscale phenomena and has many applications in meteorology and geology of the Martian environment.

1.1 Near-surface mesoscale phenomena

Regional, diurnal and seasonal variations of surface temperature are particularly large on Mars [Kieffer et al., 1976, Sutton et al., 1978]. In most cases, the low atmospheric density and heat capacity lead to negligible contributions of sensible heat flux (energy exchange between the atmosphere and surface due to molecular conduction and turbulence) in the martian surface energy budget [Sutton et al., 1978]. Consequently, the martian surface remains close to radiative equilibrium [Nayvelt et al., 1997, Savijärvi and Kauhanen, 2008, their Figure 2]. From a mesoscale point of view, this surface radiative equilibrium yields intense near-surface circulations, either driven by contrasts in topography (subsection 1.1.1) or soil thermophysical properties (subsection 1.1.2).

1.1.1 Phenomena related to topography

Near the Martian surface at radiative equilibrium, daytime warming and nighttime cooling cause the vertical profiles of atmospheric temperatures to be respectively highly unstable (superadiabatic) and ultra-stable. In terrains with uneven topography, this imposes terrain-following behaviour of atmospheric temperature, which creates local pressure gradients along slopes Mahrt [1982], Parish [2003]. These conditions, often described by the "slope-buoyancy" terminology, cause the air to accelerate upslope during the afternoon (anabatic winds) and downslope during the night (katabatic winds). Katabatic acceleration is larger for steeper slopes and greater near-surface temperature inversions [Spiga, 2010, and references therein]. Superadiabatic conditions near the surface are the main driver for strong anabatic winds. Those winds are not the strongest over the

steepest flanks but over gently-sloping terrains; slope must be steep enough for slope acceleration to be significant, but not too steep to optimize exposure to incoming sunlight. This usually results in lower velocity for afternoon anabatic winds compared to nighttime katabatic winds [Savijärvi and Siili, 1993].

Anabatic and katabatic winds are ubiquitous in the Martian environment close to topographical obstacles, and over gently-sloping plains when ambient winds are weak enough. Given the spectacular topographical contrasts and strong radiative control observed on Mars, the fact that the Martian environment is conducive to such winds has been acknowledged before in-situ missions were ever sent Gierasch and Sagan [1971]. Strong near-surface inversions yield martian katabatic wind magnitudes that are two to three times greater than on Earth (for a fixed slope steepness) despite the much lower gravity on the Red Planet Blumsack et al. [1973]. This was confirmed through mesoscale modeling [Ye et al., 1990, Savijärvi and Siili, 1993, Tyler et al., 2002, Rafkin and Michaels, 2003, Spiga and Forget, 2009, Savijärvi and Määttänen, 2010]. All models showed that, at various seasons and locations in the vicinity of craters and mountains, near-surface slope winds are repetitively predominant over background winds imposed by large-scale pressure gradients [this has also been confirmed through simulations with high-resolution GCMs Spiga and Lewis, 2010]. The only notable exception is the dust storm season. Haberle et al. [1993] suggested that near-surface slope winds are weaker when atmosphere is dustier (which, incidentally, acts as a negative feedback on dust lifting). In that sense, as far as slope winds are concerned, the closest terrestrial analog to Mars is Antarctica in situation of clear skies Parish and Bromwich [2007]. Polar regions on Mars are also conducive to strong katabatic winds [Kauhanen et al., 2008, Spiga et al., 2011], but contrary to Earth it is not necessarily the location on the planet where those events are the most intense.

Figure 13 from Tyler et al. 2002

Slope wind modeling naturally focussed on the most prominent topographical obstacles on Mars; this is the case for the Valles Marineris canyon, where some of the steepest slopes on Mars can be found. Strong afternoon canyon outflow results from upslope winds, while during the night, winds reverse to downslope directions, inducing an inflow into the canyon. The overall structure of the slope winds system around Valles Marineris is basically the same in the independent studies by Tyler et al. [2002], Toigo and Richardson [2003], Rafkin and Michaels [2003], Richardson et al. [2007], Spiga and Forget [2009]. The amplitudes of the thermally-driven Martian slope winds in the Valles Marineris region are in the range $25 - 35$ m.s^{-1} in the afternoon and $30 - 40$ m.s^{-1} in the night, while their vertical component ranges between 5 to 10 m.s^{-1}, and local maxima of vertical velocity correlate with topographic gradients. Near-surface winds are actually part of general recirculation of the atmospheric mass around the topographical obstacles. Cross-sections of the Valles Marineris canyon circulation along a given latitude also indicate that the near-surface anabatic winds are associated with a compensating downwelling of lesser amplitude in the center of the canyon, a few kilometers above the surface [Rafkin and Michaels, 2003]; the situation is reversed for katabatic winds. The uneven topography of Valles Marineris does not only drive powerful slope winds, but also acts as a mechanical obstacle and yields "channeling" of the atmospheric flow Toigo and Richardson [2003], Rafkin and Michaels [2003], Spiga and Forget [2009].

Make a new figure by combining Figures 4 + 7 from Spiga et al.

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Olympus Mons and the Tharsis volcanoes are also preferential sites to study slope winds. Rafkin et al. [2002] showed that anabatic winds over Arsia Mons could reach 40 m s^{-1} and explain spiral dust clouds observed through imagery onboard the Mars Global Surveyor spacecraft (see section **??**). Those anabatic winds have also been found to play a significant role in forming the summer afternoon clouds over Tharsis volcanoes [Michaels et al., 2006, Spiga and Forget, 2009]. Spiga et al. [2011] studied through mesoscale modeling the katabatic winds on the slopes of Olympus Mons. Figure **??** shows temperature and wind profiles in the near-surface atmospheric layer above two locations at the same longitude, one over Olympus flanks and one over surrounding flat plains. Over the flanks of Olympus Mons, the vertical profiles of temperature and wind indicate to first order Prandtl-like slope wind regime, arising from quasi-equilibrium between katabatic acceleration and near-surface friction [e.g. Mahrt, 1982]. The katabatic wind layer extends up to 1 km above the surface over the Olympus slope, with horizontal component reaching 38 m s^{-1} and vertical component reaching 14 m s^{-1}. As shown by Spiga et al. [2011], such katabatic winds over Olympus Mons exert a strong thermal influence on the Martian atmosphere and surface, which can overwhelm radiative contributions: not only their vertical component results in adiabatic compression and heating of the atmosphere, but their horizontal component enhances the downward sensible heat flux. The latter effect allow the warmer atmosphere obtained through the former effect to heat the surface significantly (the reverse phenomena with cooler atmosphere cooling the surface is also true for anabatic winds). This explains why, according to nighttime measurements, the martian surface is up to +20 K warmer on slopes than on surrounding plains in the Olympus Mons/Lycus Sulci region, with an apparent correlation between thermal signatures and slope steepness. A corollary is that surface radiative equilibrium does not hold everywhere on Mars, especially over slopes: neglecting the contribution of martian atmospheric winds in the surface energy budget could have adversely affected thermal inertia retrievals [e.g., Putzig and Mellon, 2007] to the point that artificial (wind-induced) structures correlated with slopes would appear. This exemplifies that slope winds are a key component of the Martian system, with applications on geology too.

Figures 13 from Greeley et al. 2003

Unfortunately, quantitative measurements of slope winds are seldom available, especially over terrains with uneven topography where those are the most prominent. Geological features (dunes or streaks) on Martian craters and mountains are thought to provide indirect evidence of repetitive nighttime katabatic inflow into craters, in good agreement with mesoscale model predictions Kuzmin et al. [2001], Fenton et al. [2005], Greeley et al. [2003, 2008], Toyota et al. [2011]. Nighttime water ice cloud cover in areas of complex topography [e.g. Tharsis plateaus, see Wilson et al., 2007] is consistent between observations and mesoscale models, the latter showing dominant influence of katabatic winds in cloud formation [Spiga and Forget, 2009]; as far as daytime dust and water ice clouds are concerned, Rafkin et al. [2002] and Michaels et al. [2006] have shown how mesoscale predictions in areas where slope winds are prominent are in agreement with available observations. Near-surface wind measurements to date were acquired on relatively flat terrains where it is difficult, though not impossible as shown e.g. by Leovy [1985] with Viking Landers (VL) and by Taylor

et al. [2008] through the "telltale" experiment onboard Phoenix, to separate the circulation caused by large-scale slopes from other contributions. Savijärvi and Siili [1993] showed through idealised two-dimensional mesoscale simulations that stronger large-scale forcings at the low-latitude Viking 1 site reverse the diurnal turning of winds into backing, while at the higher latitude Viking 2 site with lower large-scale contribution, the combination of Coriolis and slope accelerations leads to direct veering throughout the day. The fact that katabatic circulation over moderate Martian slopes is constrained by large-scale circulation, notably thermal tides, is further supported by high-resolution general circulation modeling [Spiga and Lewis, 2010] and three-dimensional mesoscale simulations [Toigo and Richardson, 2002] compared to Viking and Pathfinder observations. It is clear that wind measurements in uneven topographical areas on Mars would be useful to unambiguously detect repetitive, intense, clear-cut slope winds.

1.1.2 Phenomena related to thermal contrasts

1.2 Mesoscale waves

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